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May 11, 1995

Dr. Jack Kaye, Manager
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Washington, DC 20546

Dear Jack:

The purpose of this letter is to inform you of accomplishments during the second year of our NASA Contract (NASW-4844) entitled 'Dynamical Meteorology of the Equatorial and Extratropical Stratosphere' and to describe plans for the coming year. A budget for the next year is also attached.

*a. Summary of accomplishments*

The project is an observational study of large-scale waves, mean flow oscillations, interannual variability and trends in the upper troposphere, stratosphere, and mesosphere. Presently, rawinsonde data are being used together with gridded ECMWF and NMC analyses and outgoing longwave radiation (OLR) to elucidate the climatology and variability of equatorial waves, quasi-biennial oscillation, monsoon circulations, and polar vortex in winter. Objectives of the research include a better understanding of (i) processes that regulate transport and wave propagation within the tropics and tracer exchange between tropics and midlatitudes; (ii) coupling mechanisms between extratropical troposphere and stratosphere that influence stratospheric interannual variability, particularly in Northern hemisphere winter; (iii) dynamical interactions between the tropical and extratropical stratosphere, and (iv) stratosphere-troposphere (S/T) exchange.

In the second year of this Contract, analysis of tropical rawinsonde data was extended to include stations at all latitudes (from pole to pole) satisfying certain criteria for the volume and quality of data and the regional importance of each station. Altogether 984 stations are currently being used, and the dataset extends from 1 January 1973 to 21 January 1995 (our archive is updated once per year). The source data were processed into station time series (interpolated to 4x daily) and various statistics were compiled, such as monthly mean winds and temperature, and a grand climatology. We also revised the processing code to extract dewpoint depression for the purpose of studying upper tropospheric water vapor in the future. In recent years our goal has been to understand the vertical and horizontal structure, propagation and interannual variability of Rossby-gravity waves over the tropical Pacific (period 3-6 days) combining rawinsonde data with ECMWF data using principal component analysis techniques. This part of the investigation will be continued by including all longitudes of the tropical belt. Last year we concentrated primarily on the climatological



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distributions of wind and temperature. This was motivated by my observation of several new and interesting features of climatological flow in the tropical and subtropical upper troposphere and lower stratosphere. These features include, among others: (i) a semiannual oscillation in the tropical upper troposphere over the Eastern hemisphere; (ii) evidence of meridional velocity layers in the winter tropics, apparently due to a superposition of Hadley and rotational circulation induced by monsoon convection; and (iii) penetration of monsoon circulations into the summer lower stratosphere. The last item was studied intensively last year, and a journal publication will appear soon (Dunkerton, 1994). This paper was also motivated by Ping Chen's discovery of S/T exchange in connection with the Asian summer monsoon. My work with rawinsondes (1973-1995) and ECMWF data (1985-1992) supports Chen's study as it provides a 'ground-truth' estimate of monsoon penetration into the lower stratosphere using a much longer time series. In addition to their role in S/T exchange, monsoon circulations advect tropical volcanic aerosols into midlatitudes. (iv) In the lower stratosphere at solstices, rawinsonde climatologies show evidence of a strong potential vorticity gradient at the equator (most intense in the QBO west phase) thought to coincide with an equatorial 'barrier' to tracer transport. This equatorial barrier is not to be confused with subtropical and polar vortex barriers associated with the midlatitude surf zone.

In order to compare rawinsonde data with ECMWF analyses and to construct cross sections of meteorological fields, an analysis scheme was devised to map climatological rawinsonde data onto a regularly spaced longitude-latitude grid extending from pole to pole, using Barnes' algorithm with anisotropic weighting (Dunkerton, 1994). Although the time periods and analysis methods are quite different, rawinsonde and uninitialized ECMWF climatologies show very good agreement at all mandatory levels from 1000 to 10 mb. Gaps in rawinsonde analyses exist over the eastern Pacific and midlatitude Southern hemisphere oceans. Away from these data voids, rawinsonde coverage is adequate to construct reliable latitude-height cross sections of winds and temperature. Rawinsonde data may also be used to validate ECMWF analyses. One interesting byproduct of this investigation was our discovery that tropical tropopause temperatures in early initialized ECMWF analyses were too warm, by about 5 K, relative to rawinsondes. This problem diminished in later ECMWF data, the uninitialized fields after 1985 showing better agreement. For winds, the two sets of ECMWF analyses are quite similar, except for greater horizontal finestructure in the uninitialized dataset.

Our analysis lays the foundation for a comprehensive study of the tropical and subtropical upper troposphere, tropopause region, and lower stratosphere, so that processes affecting photochemistry and transport can be better understood. The regions of interest to us lie above the range of altitudes described in historical atlases of tropical meteorology.

Eastward propagating convection at the equator was studied in collaboration with Dr. Frank Crum (formerly a postdoc of mine at NWRA, now at Goddard). Ten years of OLR data were used to describe the propagation of tropical intraseasonal oscillations (period 30-60 days) and their interaction with higher frequency convection (period 2-15 days). We found a strong peak in the phase speed spectrum of equatorial OLR around 10-12 $ms^{-1}$, distinctly faster than that of the TIO, and possible evidence of enhanced synoptic convection in the active phase of the TIO. Another spectral peak was found in the OLR space-time spectrum possibly related to stratospheric Kelvin waves. Eastward propagating convection is most apparent at the equator in Northern spring, coincident with the preferred time of QBO phase transitions at 50 mb.

The current NASA Contract is providing half-time support for Dr. Xinhua Cheng. Dr. Cheng and I, together with Dr. Mark Baldwin of NWRA, are using 30 years of NMC data to investigate interannual, intraseasonal, and high-frequency variations of stratospheric circulation in Northern hemisphere winter and their coupling with the troposphere. The primary method of analysis is rotated singular value decomposition (RSVD), a technique developed by Cheng and Dunkerton (1994). Temporal filters were designed to elucidate coupled modes of variability on various timescales of interest. (i) Our preliminary analysis (reported in two publications listed below) began with interannual variations and concentrated on the known patterns of tropospheric variability at 500 mb, of which only one (the North Atlantic Oscillation) is significantly coupled to the stratospheric flow on seasonal and interannual timescales. As shown by Baldwin *et al* (1994), influence of the NAO-like pattern on the lower stratosphere exceeded that of the QBO in 1964-93 (the QBO's effect is dominant in the middle and upper stratosphere). Knowledge of the tropospheric state is evidently essential to the interpretation and prediction of stratospheric interannual variability, although the exact cause of this coupling is yet to be understood. Part of the connection may involve a modulation of the upper tropospheric 'mean flow' for planetary waves propagating upward, and part may involve a downward influence of the stratosphere on the troposphere. (ii) On intraseasonal timescales, the tropospheric patterns responsible for planetary waves entering the lower stratosphere have been identified by us. We are presently examining Eliassen-Palm fluxes to determine how combinations of coupled modes conspire to produce large fluxes that subsequently decelerate the polar vortex. Lag correlations suggest that coupled modes of variability are best defined when the troposphere leads the stratosphere by a few days, consistent with upward wave propagation. (iii) On relatively fast timescales (2-6 days), we identified coupled patterns associated with transient baroclinic instabilities that influence the winter lower stratosphere to a height of at least 50 mb. These waves are evanescent in the midlatitude stratosphere, with small amplitude and little phase tilt, but are important for 'microbreaking' at the periphery of the polar vortex and may affect the permeability of the vortex edge in very lower stratosphere.

*b. Journal publications*

Journal publications include the following:

Baldwin, M.P., X. Cheng, and T.J. Dunkerton, 1994: Observed correlations between winter-mean tropospheric and stratospheric circulation anomalies. *Geophys. Res. Lett., 21*, 1141-1144.

Dunkerton, T.J., and M.P. Baldwin, 1994: Observation of 3-6 day meridional wind oscillations over the tropical Pacific, 1973-1992: horizontal structure and propagation. *J. Atmos. Sci.*, in press.

Dunkerton, T.J., and F.X. Crum, 1994: Eastward propagating ~2-15 day equatorial convection and its relation to the tropical intraseasonal oscillation. *J. Geophys. Res.*, submitted.

Cheng, X., and T.J. Dunkerton, 1994: Orthogonal rotation of spatial patterns derived from singular value decomposition analysis. *J. Climate*, in press.

Dunkerton, T.J., 1994: Evidence of meridional motion in the summer lower stratosphere adjacent to monsoon regions. *J. Geophys. Res.*, in press.

*c. Plans for the coming year*

In the third year of Contract NASW-4844 we will continue the investigation of equatorial waves in rawinsonde, ECMWF, and OLR data, extending it to include all longitudes of the tropical belt. Insofar as the scope of the waves study precludes its completion in the third year, our immediate objectives will be (i) to extend the OLR dataset through 1995; (ii) to merge initialized and uninitialized ECMWF analyses into a single dataset so that the available record extends from 1980-1995 (this will pave the way for our eventual replacement of these data with fields from the ECMWF reanalysis project); (iii) alter the processing algorithms for multivariate principal component analyses to accommodate the lengthened record and to extend the calculation to all longitudes using regional subgrids as in Dunkerton and Baldwin (1994).

The features identified in rawinsonde climatological analyses will be compared to ECMWF analyses, and organized for presentation into several additional publications. Once our preliminary study of the climatology is complete, attention will be given to the formation of monthly mean rawinsonde analyses. This will enable studies of interannual variability to be performed (e.g., of QBO, tracer barriers, monsoon circulations) with rawinsonde data on a regularly spaced grid, supplementing the description of interannual variability attainable at individual stations and allowing a critical assessment of ECMWF analyses in the regions of interest (tropical and subtropical upper troposphere, tropopause region, and lower stratosphere). Although most of this investigation will be undertaken in subsequent years, the groundwork for construction of monthly mean analyses will be laid in the third year of the current Contract. Tentatively, the method will be as follows. Climatological analyses already obtained will be employed as a 'first guess' field in each respective month, and statistical optimal interpolation (SOI) will be used to obtain analyses for individual months. This procedure is analogous to that of operational weather centers where daily analyses are constructed from a forecast model's first guess, and SOI is used (together with weight functions derived from daily error statistics) to obtain the next analysis. In the present case, weight functions will come from monthly mean statistics, and a pre-derived grand climatology constitutes the first guess. (Note that the grand climatology did not benefit from a first guess, and despite our best effort, it may not be statistically optimum.) In addition to providing a regular grid of rawinsonde data for each month, the above technique may allow some refinement of the grand climatology itself.

Results from the climatology study will be used in a joint investigation with Dr. Lenny Pfister of NASA Ames to examine the seasonal, intraseasonal, and longitudinal variations of convective gravity wave excitation near the tropical tropopause.

Work will begin on a compilation of a semiannual oscillation (SAO) climatology using rocketsonde data in conjunction with several other datasets (SME, LIMS, SAMS, PMR, UARS and radar data). Several scientists have expressed interest in such a climatology that would serve as a reference for future studies, e.g., of photochemistry and transport in the upper stratosphere, and stratosphere-mesosphere coupling. A joint publication with Drs. Rolando Garcia, Todd Clancy, Susan Avery, Bob Vincent and Ruth Lieberman is presently anticipated.

Interannual variability of the Northern hemisphere stratosphere will be investigated in collaboration with Drs. Cheng and Baldwin. An attempt will be made to determine whether the coupling observed on interannual timescales originates primarily in the troposphere or stratosphere. For example, the intraseasonally filtered data may be windowed according to the phase of the NAO-like interannual pattern to determine if the latter is responsible for modulating the upward propagation of planetary waves. (We have already seen evidence that this pattern significantly modulates baroclinic instabilities in the troposphere, but it is hard to imagine that this is particularly relevant to the stratospheric polar vortex; the vortex is mainly sensitive to planetary waves.) The manner in which Eliassen-Palm fluxes are related to intraseasonal modes will be studied by compositing EP flux with respect to the phase of these modes. Alternatively, the RSVD method will be employed (between EP flux and 500 mb geopotential) to directly determine which phase coincides with maximum upward flux. Finally, the importance of tropospheric baroclinic instabilities to microbreaking along the polar vortex periphery will be assessed as a function of altitude.

Sincerely,

TJ Dunkerton

Timothy J. Dunkerton
Principal Investigator

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An observational study is performed of large-scale waves, mean flow oscillations, interannual variability and trends in the middle atmosphere, using upper-air rawinsonde, rocketsonde, and satellite data together with global gridded analyses from NMC and ECMWF. The purpose is to elucidate the climatological behavior of equatorial waves, quasi-biennial and semiannual oscillations, and extratropical wintertime flow. Objectives of the research include a better understanding of processes that regulate transport within the tropics and tracer exchange between tropics and extratropics, processes such as troposphere-stratosphere coupling that influence stratospheric interannual variability, particularly in northern hemisphere winter, and dynamical interactions between the tropical and extratropical stratosphere. Progress relating to equatorial wave excitation and propagation, QBO and seasonal cycle morphology, rocketsonde temperature trends, and stratosphere-troposphere coupling are summarized in this report.

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